Geodesy and Geodynamics 2012,3(3):17-22

http://www.jgg09.com
Doi:10.3724/SP.J.1246.2012.00017

Ionospheric anomaly before the 2011 Tohoku *M*w 9.0 earthquake

Yang Jian[1,2,3], Zhou Yiyan[1,2,3] and Su Fanfan[1,2]

[1] *Key Laboratory of Earthquake Geodesy, Institute of Seismology, China Earthquake Administration, Wuhan* 430071, *China*

[2] *Wuhan Base of Crustal Dynamics, China Earthquake Administration, Wuhan* 430071, *China*

[3] *School of Geodesy and Geomatics, Wuhan University, Wuhan* 430079, *China*

Abstract: Using Computerized Ionospheric Tomography (CIT) in combination with GPS observations from the Crustal Movement Observation Network of China (CMONOC), this study reconstructed the electron density distributions over China before the 2011 Tohoku *M*w 9.0 earthquake and discovered a prominent ionospheric anomaly on March 8, 2011. Analysis of the solar-terrestrial space environment around the time of the Tohoku earthquake indicated that the March 8 ionospheric anomaly was likely related to the earthquake. Finally, the paper discusses the drift of the ionospheric anomaly, which was inferred from the anomaly being observed by GPS reference sites in China.

Key words: ionosphere; tomography; ionospheric anomaly; Tohoku earthquake; CMONOC

1 Introduction

Since Davis and Baker first found a prominent ionospheric disturbance before the great Alaskan earthquake in 1965[1], geoscientists have had significant interest in seismo-ionospheric anomalies as a type of earthquake precursor. Researchers have summarized some of the regular patterns of seismo-ionospheric anomalies based on these investigations[2-4].

The disastrous Tohoku earthquake, which occurred on March 11, 2011 near the east coast of Honshu, Japan (epicenter: 38.297°N, 142.372°E) with a moment magnitude of 9.0[5], was one of the most significant earthquakes in recent years. Ionospheric anomalies prior to this earthquake have been analyzed by several researchers. Zhu Fuying and Wu Yun[6] inspected the temporal variations of ionospheric TEC before the earthquake and found anomalous increases in TEC on March 5 and 8, 2011. Chen Biyan et al[7] reconstructed electron densities during a 21-day time period prior to the Tohoku earthquake using Computerized Ionospheric Tomography (CIT) and concluded that the abnormal changes in electron density, which decreased on February 28 and increased on March 2 to 4, 2011, were likely the precursors of the Tohoku earthquake. Yao Y B et al[8] used multiple observation methods to investigate the ionospheric variations before the Tohoku earthquake and considered that the obvious ionospheric anomaly from 15:00LT to 19:00LT on March 8 could be regarded as the precursor of this event.

With the expansion of the Crustal Movement Observation Network of China (CMONOC), GPS observations from approximately 260 reference sites can now be applied to study the ionosphere above China. In this paper, we use CMONOC GPS observations to reconstruct the electron density distributions before the Tohoku earthquake by means of CIT. Then, we analyze the features of the ionospheric variations according to the reconstructed results. Based on the above procedure, we can assess the applicability of CIT to the field

Received: 2012-06-27; Accepted: 2012-07-10

Corresponding author: Yang Jian, E-mail: xintai-sense@163.com

This study is supported by the National Natural Science Foundation of China (41174030) and the Director Foundation of Institute of Seismology, China Earthquake Administration (IS200916012).

of earthquake prediction.

2 Fundamentals of computerized ionospheric tomography

As discussed by Austen[9], TEC can be expressed as an integral of the electron density along a ray path in the ionosphere and is given by:

$$TEC = \int Ne\,dl \tag{1}$$

Where Ne is the electron density of ionosphere and L is the integration path. Formula (1) implies that the electron density distribution of the ionosphere in space can be reconstructed if TEC values have been provided. For numerical calculation purposes, the study area of the ionosphere is divided into several blocks (Fig. 1). Then, a linear equation set can be obtained from formula (1) as follows:

$$(TEC_i)_i^m = 1 = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = AX \tag{2}$$

Where $x_j (j = 1, 2, \cdots, n)$ represents the mean electron density in block j and element a_{ij} in operation A is the propagation distance of signal i through block j. TEC_i refers to the computed total electron content. The dual-frequency pseudo-range combination of GPS is used to obtain TEC, which is given by:

$$TEC = \frac{f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)}(P_2 - P_1 - B) \tag{3}$$

Where f_i and $P_i (i = 1, 2)$ are the frequency and pseudo-range observation in the L_i band, respectively, and B is the differential code bias in the GPS system, which can be estimated by using a global ionospheric model.

For the solution of the equation set expressed as formula (2), we introduce an iterative method that is referred to as the Algebraic Reconstruction Technique (ART). The ART takes an electron density distribution derived from an empirical ionospheric model, such as the International Reference Ionosphere (IRI), as the initial rough solution of the above equation set and adjusts the rough solution iteratively until it converges using the following iterative formula:

$$x_j^{(k+1)} = x_j^{(k)} + \lambda \frac{y_i - \sum_{l=1}^{n} a_{il} x_l^{(k)}}{\sum_{l=1}^{n} a_{il}^2} a_{ij} \quad j = 1, 2, \cdots, n \tag{4}$$

Where λ is the relaxation factor and i equals $MOD(k,$

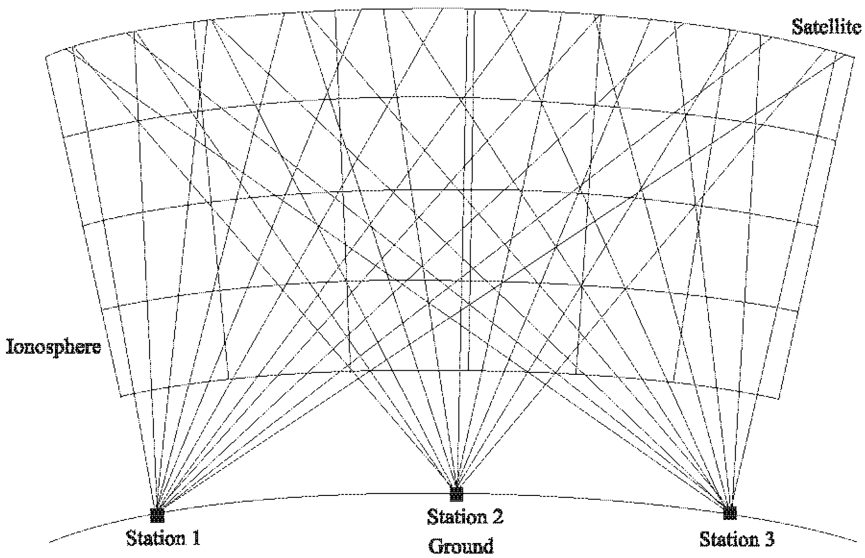

Figure 1 Schematic diagram of computerized ionospheric tomography

$m) + 1$, in which k denotes the iteration number. By employing the above iterative formula, we can obtain the final solution of formula (2), which satisfies the least norm criterion and represents the electron density distribution of the ionosphere.

3 Seismo-ionospheric anomaly of the Tohoku earthquake detected by CIT

Using GPS observations from CMONOC, we investigated the 15-day ionospheric variations above China before the Tohoku earthquake. To reconstruct the electron density distributions via CIT, we chose the GPS reference sites located in the area of interest (depicted with a red frame in figure 2) to form the observation network for tomography. Because approximately 260 reference sites have been put into service, we were able to reconstruct electron density distributions with a higher level of precision.

By analyzing the ionospheric variations before the Tohoku earthquake, we found an apparent increase in the electron density on March 8, 2011. This increase is visible in figures 3, 4 and 5, which are slice diagrams of the electron density distribution in the reconstructed area at 10:00UT on March 7, 8 and 9, respectively. The time at which the ionospheric anomaly occurred was consistent with the conclusions of Zhu Fuyin[6] and Yao Y B[8].

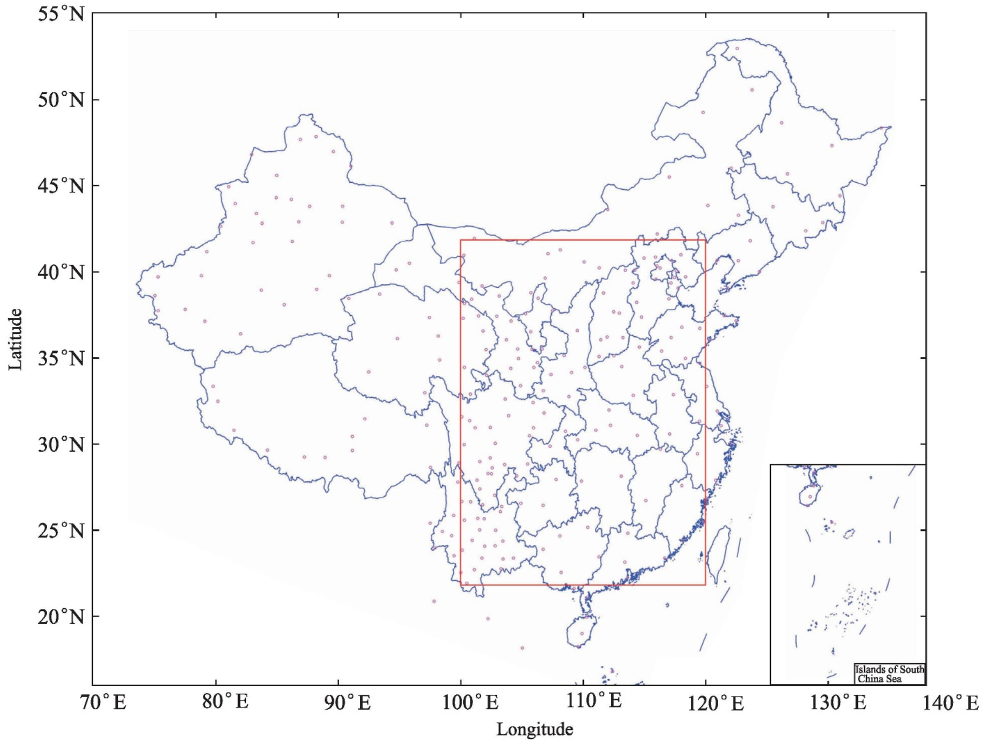

Figure 2 Distribution of the reference sites in the reconstructed area

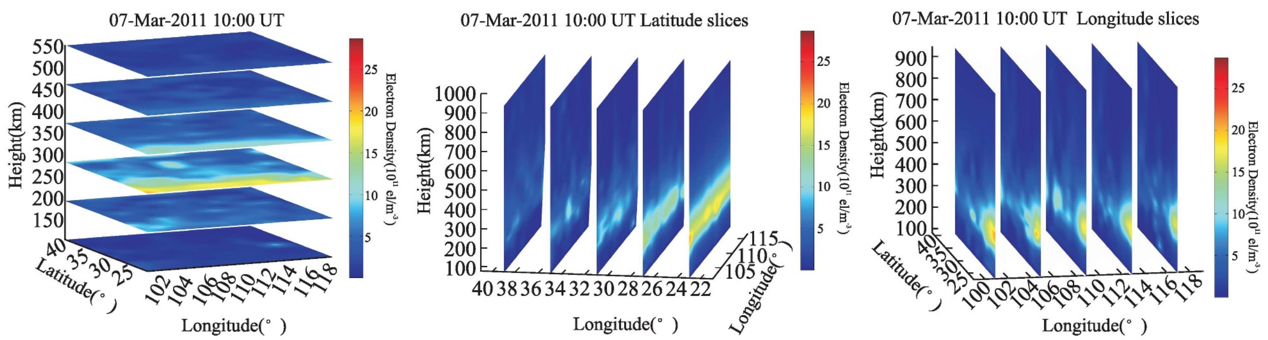

Figure 3 Slice diagrams of the electron density distribution in the reconstructed area at 10:00UT on March 7, 2011

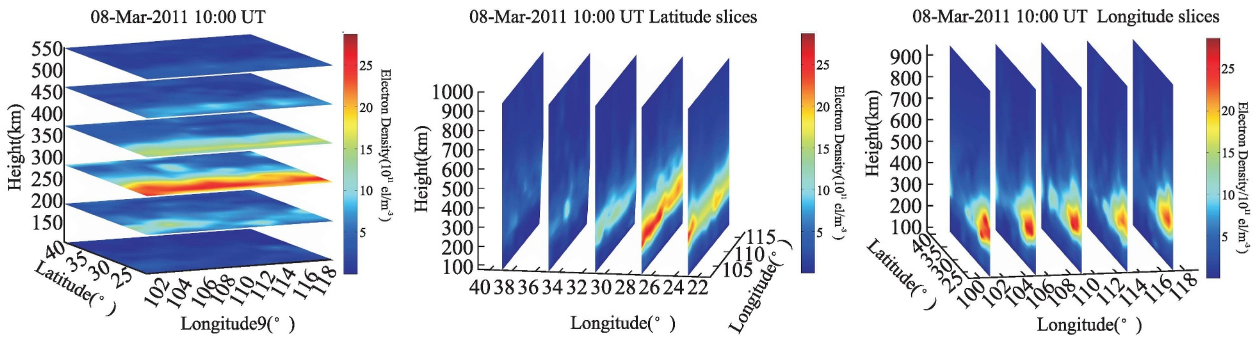

Figure 4 Slice diagrams of the electron density distribution in the reconstructed area at 10:00UT on March 8, 2011

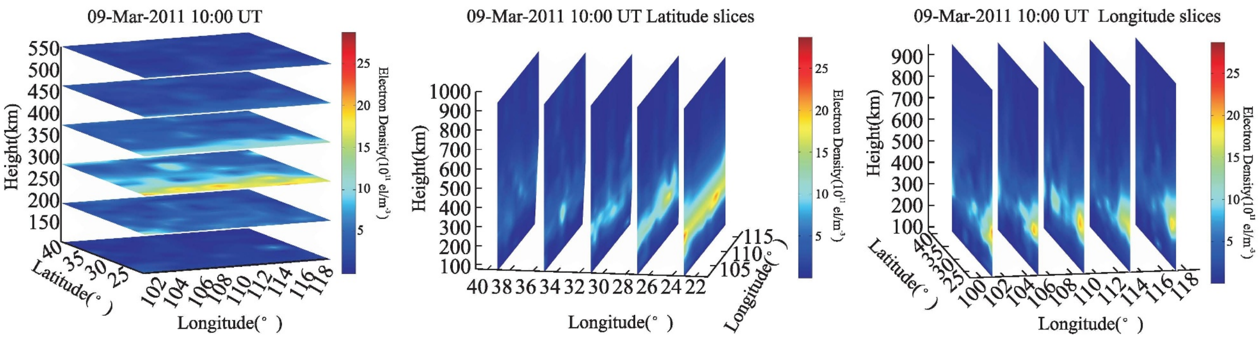

Figure 5 Slice diagrams of the electron density distribution in the reconstructed area at 10:00UT on March 9, 2011

From figure 4, we noted that the peak electron density had more than doubled, representing an abnormal change. The anomaly area was approximately bounded by spatial dimensions of east longitude 100° – 120° and north latitude 22° – 32°, with a height of 200 – 400 km.

We also investigated the geomagnetic Dst and Kp indices around the time of the Tohoku earthquake, as shown in figures 6 and 7, respectively, to determine whether the abnormal increase in the electron density shown in figure 4 might be linked to the Tohoku earthquake. We found that no strong geomagnetic storms had taken place before the earthquake, particularly on March 8, when the geomagnetic activity was relatively weak. Considering the solar-terrestrial space environment around the time of the earthquake synthetically, we inferred that the abnormal increase in the electron density above China on March 8 may have been caused by the Tohoku earthquake.

As discussed above, a significant ionospheric anomaly appeared three days before the Tohoku earthquake that was very likely due to the earthquake pregnant tectonics. This anomaly was observed by the GPS reference sites in China. However, experience with seismo-ionospheric anomalies suggests that anomalies are often generated near the epicenter. Thus, it was reasonable for us to infer that the ionospheric anomaly should be able to move from east to west. To verify our inference, we inspected the VTEC variations above China prior to the Tohoku earthquake based on Zhou's computing method for the ionospheric VTEC[10]. The result of the VTEC anomaly on March 8, 2011 is depicted in figure 8. When focusing on the VTEC anomaly at 10:00UT, the figure clearly indicated that the boundary of the VTEC anomaly was consistent with that of the electron density anomaly. From figure 8, we also found that the VTEC anomaly was changing in the period from 8:00UT to 14:00UT and moving from east to west with the Earth's rotation. This phenomenon, which we refer to as the drift of the ionospheric anomaly, has also been observed in other earthquakes, such as those in Wenchuan[11] and Yushu[12]. These repeated observations indicate that drifting may be typical of ionospheric anomalies. The physical mechanism of this drift is still unknown and should be researched further in the future.

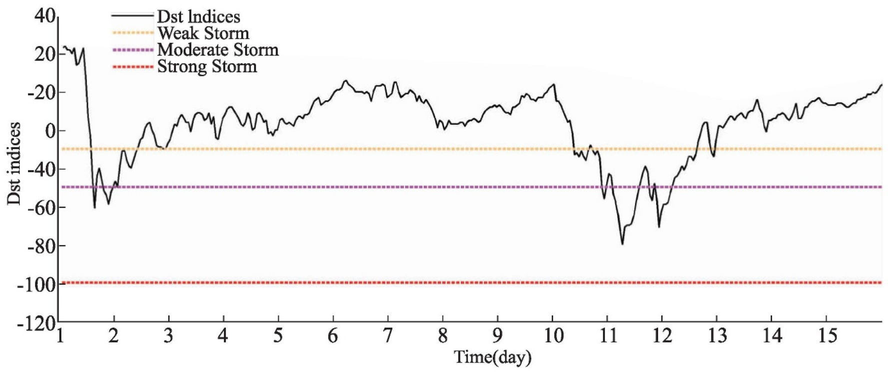

Figure 6 Dst indices on March 1 to 15, 2011

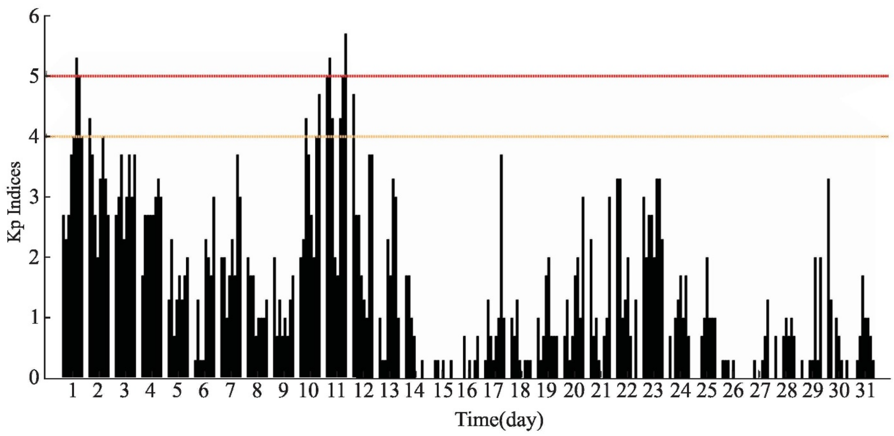

Figure 7 Geomagnetic Kp indices in March 2011

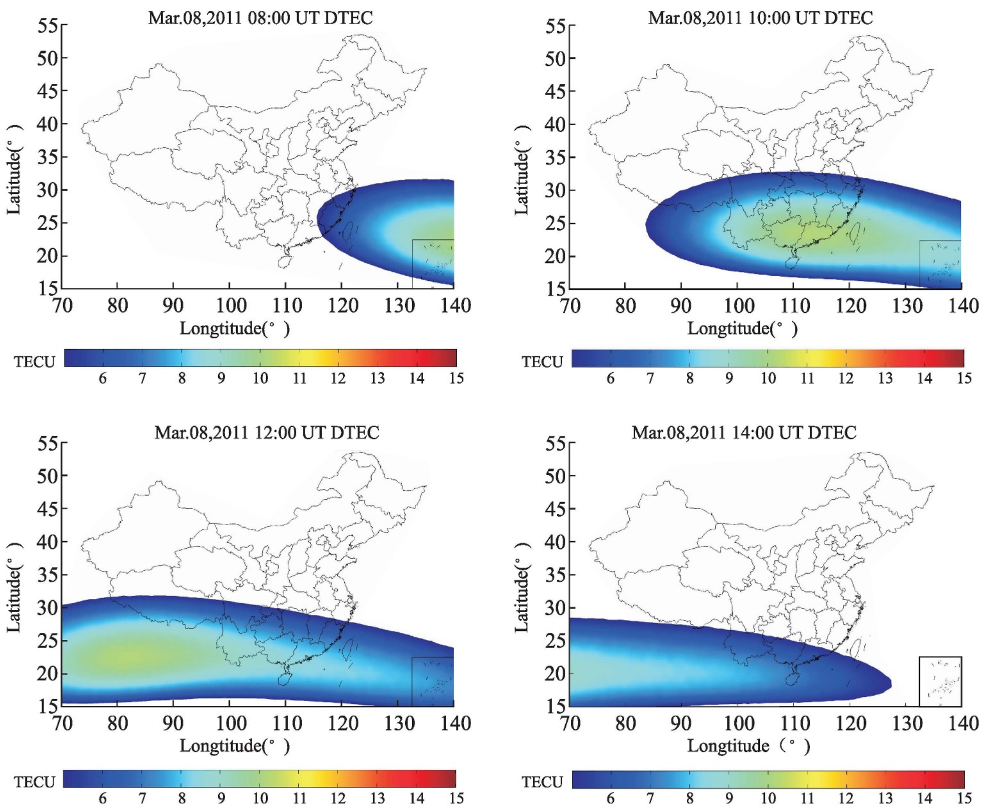

Figure 8 Distribution of the ionospheric VTEC anomaly around the epicenter at 8:00UT, 10:00UT, 12:00UT and 14:00UT on March 8, 2011

4 Conclusion

Earthquake prediction is a worldwide problem. To be able to make reliable predictions, researchers have explored many earthquake precursors, such as crustal deformations, hydro-chemical anomalies, geoelectric and geomagnetic effects. The ionospheric anomaly is a new type of seismic precursor that has become the topic of numerous studies in recent years. Former studies on seismo-ionospheric anomalies focused on VTEC variations, which represent overall variations in electron density in the vertical direction but cannot provide three-dimensional details of the ionospheric anomalies.

In this paper, we introduced CIT to inspect the three-dimensional structure of the ionosphere. We used GPS observations from the CMONOC to reconstruct the 15-day electron density distributions above China before the Tohoku earthquake. By comparing the different electron density distributions at the same coordinate universal time of 10 : 00 on different dates, we found that the ionosphere increased abnormally on March 8, 2011. Analysis of the geomagnetic Dst and Kp indices around the time of the Tohoku earthquake indicated that the ionospheric anomaly was very likely related to the earthquake. The results of this study indicate that CIT has potential for being widely applied in the field of earthquake prediction.

Previous studies on seismo-ionospheric anomalies have confirmed that ionospheric anomalies always appear near the epicenter of the earthquake. Unlike previous studies, in this paper, we used observations from GPS reference sites in China to analyze the ionospheric anomaly that was linked to the earthquake in Japan and obtained significant results. Our results indicated that ionospheric anomalies can drift from east to west. The drift of an ionospheric anomaly has also been observed for other earthquakes. Thus, such drifts appear to be a feature of ionospheric anomalies, and the physical mechanisms of these drifts warrant further research.

Acknowledgement

We would like to thank Crustal Movement Observation Network of China for providing continuous GPS observations. We are also grateful to NOAA National Geophysical Data Center and WDC in Tokyo for providing geomagnetic indices.

References

[1] Davies K and Baker D. Ionospheric effects observed around the time of the Alaskan earthquake of March 28, 1964. J Geophys Res., 1965, 70: 1251 - 1253.

[2] Sergey Pulinets. Ionospheric precursors of earthquakes; Recent advances in theory and practical applications. TAO. 2004, 15(3): 413 - 435.

[3] Liu J Y, Chou Y J, Shan S J, Tsai Y B, Chen Y I, S A Pulinets and Yu S B. Pre-earthquake ionospheric anomalies registered by continuous GPS TEC measurements. Annales Geophysicae. 2004, 22: 1585 - 1593.

[4] Zhu Fuying, Wu Yun, Zhou Yiyan and Lin Jian. Statistical analysis of pre-earthquake ionospheric TEC disturbance. Journal of Geodesy and Geodynamics. 2010, 30(5):19 - 23. (in Chinese)

[5] Magnitude 9. 0-NEAR THE EAST COAST OF HONSHU, JAPAN. http://earthquake. usgs. gov/earthquakes/eqinthenews/2011/usc0001xgp/.

[6] Zhu Fuying and Wu Yun. Anomalous variations in ionospheric TEC prior to the 2011 Japan *Ms*9. 0 earthquake. Geodesy and Geodynamics. 2011, 2(3): 8 - 11. Doi:10. 3724/SP. J. 1246. 2011. 00008.

[7] Chen Biyan, Dai Wujiao, Cai Changsheng, Kuang Cuilin and Liu Ying. Ionospheric anomaly detection before Japan *Ms*9. 0 earthquake by use of ionospheric tomography technology. Journal of Geodesy and Geodynamics. 2011, 31(6): 11 - 14. (in Chinese)

[8] Yao Yibin, Chen Peng, Wu Han, Zhang Shun and Peng Wenfei. Analysis of ionospheric anomalies before the 2011 *Mw*9. 0 Japan earthquake. Chin Sci Bull., 2012, 57(5): 355 - 365, doi: 10. 1007/s11434-011-4851-y. (in Chinese)

[9] Jeffrey R Austen, Steven J Franke and Liu C H. Ionospheric imaging using computerized tomography. Radio Science. 1988, 23(2): 299 - 307, doi: 10. 1029/RS023i003p00299.

[10] Zhou Yiyan, Wu Yun, Qiao Xuejun and Zhang Xunxie. Ionospheric anomalies detected by ground-based GPS before the *Mw*7. 9 Wenchuan earthquake of May 12, 2008, China. Journal of Atmospheric and Solar-Terrestrial Physics. 2009, 71: 959 - 966, doi: 10. 1016/j. jastp. 2009. 03. 024.

[11] Zhou Yiyan, Wu Yun, Qiao Xuejun, Zhu Fuying and Yang Jian. Anomalous variations of ionospheric VTEC before *Ms*8. 0 Wenchuan earthquake. Chinese Journal of Geophysics. 2010, 53(3): 556 - 566, doi: 10. 3969/j. issn. 0001 - 5733. 2010. 03. 009.

[12] Xiong Jing, Zhou Yiyan and Wu Yun. Ionospheric VTEC anomaly detected by ground-based GNSS before *Ms*7. 1 Yushu earthquake. Journal of Geodesy and Geodynamics. 2010, 30(5): 24 - 27. (in Chinese)